Applications of Spectral Analysis in Airborne Electromagnetic Data Interpretation

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Abstract

Spectral analysis of profiles of airborne electromagnetic data over thin conductive targets can be used to interpret for their depth, dip, and quality. Profiles in the space-domain are transformed to the wavenumber-domain by the application of a Fourier transform. A direct interpretation in the wavenumber-domain can then be done for the depth, dip, and quality of an anomalous body. The depth to the top of the equivalent current axis below the receiver is calculated from the slope of the amplitude spectrum decay. Dip is best determined from the phase spectrum, and quality from the spectral changes with time of measurement or operating frequency. Evidence to support the use of the spectral analysis method of interpretation can be deduced from analytical results obtained by approximating the induced current flow in a target by a single line source at the top, and from analysis of numerical modeling results. Applications of this interpretation technique are shown for several field data sets. It can also be applied to the interpretation of ground electromagnetic data.

Introduction

Airborne electromagnetic (AEM) methods constitute a relatively economical and rapid means of surveying large regions. Interpretation of AEM surveys is concerned with determining the depth, dip, and quality or conductance of any conductive targets which may be detected. A careful analysis of AEM data is warranted because of the high cost of ground follow-up work. The standard interpretation nomograms however are frequently calculated for a certain target size and/or orientation, and interpretation errors may occur if the parameters of the anomalous target do not match those of the chosen nomogram. In particular, as pointed by Ferneyhough (1985), the strike and dip of a conductor have a large effect on a correct depth interpretation for the target. The spectral analysis method of interpretation, however, allows for independent interpretations of the depth, dip, and quality of the conductor.

Spectral analysis of EM data, as used here, is similar to many uses of the method in gravity and magnetic data interpretation. Profiles of EM data obtained in the space-domain are converted to the wavenumber- or transform-domain by the application of a Fourier transform. The data is now a function of wavenumber with units of inverse meters, instead of position or meters. Data profiles measured at different observations times or operating frequencies are transformed separately. In the wavenumber-domain, a direct interpretation can be made for the depth to the equivalent current axis in the target below the receiver. Dip and quality of the conductor can also be determined. AEM field data is influenced by, and must be corrected for, the velocity of the aircraft used and the integration time constant of the receiver equipment. However, this effect is quite easily eliminated in the transform-domain. Further details of the spectral analysis method of interpretation can be found in Bartel (1988).

Modeling and Interpretation

The simplest way to approximate the response of a conductive target is to simulate it by a line source of current at or near the top of the conductor. The magnitude of the induced current in the conductor depends on the position of the transmitter and the magnitude of the measured secondary magnetic fields depends on the position of the receiver, both of which move in tandem across the wire source on a line at right angles to the wire. Thus, the horizontal magnetic field at the receiver due to a vertical dipole transmitter, which simulates the INPUT and GEOTEM AEM systems, can be written as

$$H_z(x,z) = C\frac{x+l/2}{(x+l/2)^2+z^2}\cdot\frac{z-h}{(x-l/2)^2+(z-h)^2}. \qquad (1)$$

Here C is a constant which takes into account the moments of the transmitter and receiver, conductance of the target, the frequency or time of measurement, and other factors; while x is the measurement position at the mid-point of the transmitter-receiver array which are separated horizontally by l and vertically by h, and the zero position of the profile is directly over the target which is at a depth z beneath the transmitter. Equation (1) can be transformed to the wavenumber-domain using well-known properties and formulae of the Fourier transform (e.g. Gradshteyn and Ryzhik, 1980) to yield

$$H_z(k_x,z) = C'(z,h,l)e^{\frac{ilk_x}{2}}\left[Ae^{-(z-h+il)k_x}+Be^{-zk_x}\right]; \qquad (2)$$

where A and B are complex numbers which depend on z, h and l. The amplitude spectrum derived from equation (2) consists of two decaying exponentials: one with a slope of $-z$ relating to the height of the transmitter above the wire source, and the other with a slope of $-(z-h)$, which is the height of the receiver above the wire source. Since $(z-h)<z$ for a towed-bird system (such as INPUT or GEOTEM), the predominant decay will be dependent on $z-h$ or the depth of the wire source below the receiver.

The phase spectrum is a more complicated function which is dominated by a linear drift dependent on the horizontal separation of transmitter and receiver. Empirically this drift can be removed, allowing the phase spectrum to be more easily used for interpretation purposes.

Wesley (1958) formulated the space-domain response of an infinitely conductive half-plane using dipole excitation. The responses over half-planes of various dips using the standard fixed-wing INPUT configuration given in Lazenby (1973) with a horizontal component receiver trailing a vertical dipole transmitter at a 35° angle (67 m below and 96 m behind), and a transmitter flying height of 120 m are shown in Figure 1. The transform-domain amplitude spectra in Figure 2 were derived from the model curves in Figure 1 using a sampling interval of 10 m and a 2048-point data set centered over the top of the half-plane. At high wavenumbers (>10 cycles/km), the decay rate is constant for each model and directly proportional to the depth to the top of the half-plane below the receiver. The main effect of the dip on the amplitude spectrum is changes in the shape of the spectrum at low wavenumbers (<5 cycles/km) which may be used to qualitatively estimate the dip of the conductor. The phase spectra for the same models in Figure 3 show better discrimination properties between different conductor dips after correction for the linear phase drift is made (see Bartel, 1988).

If data is taken at different observation times or frequencies, the information can be used to estimate the conductance of a thin plate target. The conductance cannot be determined directly, but rather the conductance times the shorter areal dimension (strike or depth extent) of the target. This conductance-length factor (σsL) has units of S·m. The nomogram shown in Figure 4 was developed for the fixed-wing INPUT system to determine the conductance-length factor of a target from the time decay of the amplitude spectra. The vertical scale is normalized by the amplitude of the channel 1 data so that it always equals one. The horizontal scale

INPUT - Barringer Research Ltd.; GEOTEM - Geoterrex, Ltd.

is equal to σsL in units of S·m. The different curves represent the relative magnitude (to the channel 1 response) of the amplitude spectra using the standard INPUT channels (see Lazenby, 1973, for measurement times) measured at a low wavenumber (preferably $\approx$1 cycle/km).

To use Figure 4, the interpreter should evaluate the amplitude spectra for the different channels at approximately 1 cycle/km and transfer them to logarithmic paper at the same scale as Figure 4. Normalization by the channel 1 value can be done by shifting vertically so that the channel 1 amplitude falls on the channel 1 curve in Figure 4. The relative spacing between the other channel amplitudes can be matched by a horizontal adjustment along the conductance-length axis. Once the time decay of the amplitude spectra is matched, σsL can be read on the bottom scale. The measured σsL value is invariant with respect to dip or depth of the target. Estimates of σsL from Figure 4 should be better than space-domain determinations because the spectral analysis method relies on a broad base of data that has been transformed, and it is unaffected by any migration of the peak anomaly in the space-domain.

Interpretation of field results

AEM measurements are influenced by the velocity of the aircraft and the time constant of the receiver equipment. The measured system response in the field is a convolution of the field response at discrete, static points with the step response of the equipment that can be represented as a single exponential term. Thus

$$F^*(x) = F(x) * \frac{1}{v\tau_e} e^{-x/v\tau_e} u\left(\frac{x}{v}\right); \qquad (3)$$

where $F^*(x)$ is the measured field response, $F(x)$ is the static response measured at discrete points, x is the spatial position of the aircraft along the profile, v is the aircraft velocity, and τ_e is the time constant of the EM equipment. The function $u(*)$ is the unit step function. The convolution operation in equation (3) becomes a multiplication in the wavenumber-domain. Thus, a correction to the transformed field data can be applied so that they can be correctly interpreted. For the amplitude spectrum,

$$\left|F(k_x)\right| = \left|F^*(k_x)\right| \times \left[1+(v\tau_e k_x)^2\right]^{1/2}. \qquad (4)$$

A simple correction also exists for the phase spectrum.

The measured signal in an EM system is a combination of both the true signal or message from the target and noise. The noise can be geological, instrumental, natural, or man-made in origin. A proper depth interpretation using the spectral analysis method requires that the amplitude spectrum be adequately defined at higher wavenumbers where the spectrum decays exponentially at a rate proportional to the height of the receiver above the equivalent target source. If this range is limited, the depth will most likely be underestimated. If the noise in the field response is <1% of the peak anomaly value, sufficient range in the transform-domain exists for a correct depth interpretation. Dip and conductance-length determinations are best based on the response at low wavenumbers which are little affected by noise. Filtering techniques are unusable for the spectral analysis method because both the signal and noise are considered to be wide-band.

To process field results, the field curves should be digitized at a sufficiently small interval so that aliasing will not occur and over as long a profile length as possible as long as the response from only one conductive area is covered. The data should then be smoothed, padded with zeroes to increase spectral resolution, and then have a Fourier transform applied to obtain the data in the transform-domain. The velocity correction outlined in equation (4) is then applied. Interpretation of the spectral curves in the manner outlined above can then be accomplished for the depth, dip, and conductance-length factor of the target.

Discussion

The spectral analysis method of interpretation was applied to the field results over several known mineral deposits for the fixed-wing INPUT and other AEM systems. The results agreed quite well with the known target parameters derived from drilling and mining. For a prismatic target, thin or thick, the depth of the equivalent current axis can be determined with reasonable accuracy, even though the noise in the amplitude spectrum does limit resolution. Orientation and quality of the conductor could also be determined in most cases. Having a long profile with only a single conductor response present and sampling at a fairly small spatial interval will give the best results in the transform-domain.

It can also be shown that it is possible to differentiate between different possible conductor geometries by examining the transform-domain spectra. While there may be ambiguity in the space-domain which allows several different models to be fit to the data, they can be sorted out in the transform-domain in order to choose the best model.

This method of interpretation can also be used to interpret ground EM data sets. In that case, no velocity correction [see equation (4)] is necessary. Depending on the particular ground EM system configuration used, equations and nomograms can be easily developed to interpret the data in a manner similar to the interpretation shown here for the INPUT AEM system.

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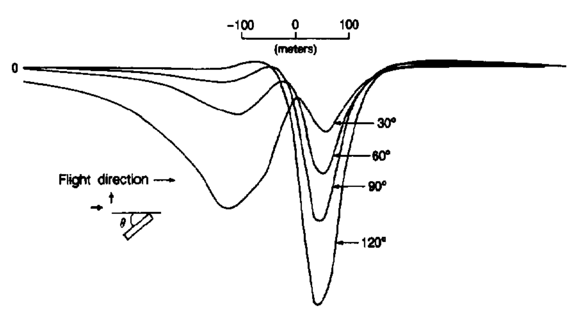

FIG. 1. Space-domain response changes with respect to dip for fixed-wing Input system over an infinitely conductive half-plane. Dip is measured clockwise from profile direction (left to right).

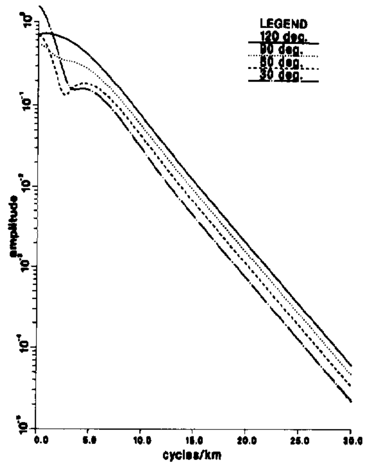

FIG. 2. Effect of dip on amplitude spectra for fixed-wing Input system.

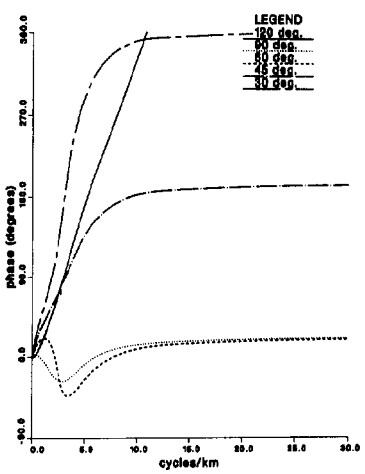

FIG. 3. Corrected phase spectra for half-planes of various dips using fixed-wing Input configuration.

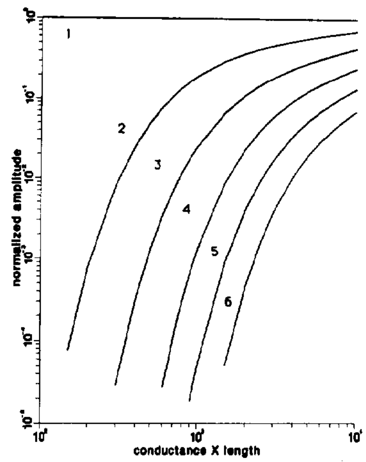

FIG. 4. Determination of conductance-length factor from time decay of amplitude spectra for fixed-wing Input system. Measurement times given in Lazenby (1973), vertical scale normalized by amplitude of first channel, and spectra measured at 1 cycle/km.